

Characterization of the Ionosphere over the South Atlantic Ocean by Means of Ionospheric Tomography using Dual Frequency GPS Signals Received On Board a Research Ship

¹Dr Pierre J. Cilliers, ²Dr Cathryn N. Mitchell, ^{1,3}Mr Ben D.L. Opperman

¹Hermanus Magnetic Observatory (HMO), Hermanus, South Africa

²Dept of Electronic and Electrical Engineering, University of Bath, BA2 7AY, UK

³Department of Physics and Electronics, Rhodes University, Grahamstown, South Africa

pjcilliers@hmo.ac.za / C.N.Mitchell@bath.ac.uk / Ben.Opperman@hmo.ac.za

ABSTRACT

This paper reports a novel approach to extend the coverage of terrestrial ionospheric measurements over a poorly characterized region of the South Atlantic Ocean, including the South Atlantic Anomaly, by using dual frequency GPS signals received on board the South African polar research ship SA Agulhas. The routes of the SA Agulhas to the South Atlantic Islands, Gough (40°17'S, 9°58'W, Mag lat 42°S) and Marion (46°52'S, 37°51'E, Mag lat 51°S) and the South African Antarctic base SANAE IV (71°40'S, 2°51'W, Mag lat 61°S) present unique locations for investigating the variability of the upper atmosphere in the high latitudes in the vicinity of the South Atlantic Anomaly and its link with the near-Earth space environment.

1.0 INTRODUCTION

The current geographical coverage of the International GNSS Service (IGS) tracking network limits the spatial and time resolution of ionospheric global models used for prediction of HF sky wave transmissions and for the prediction of scintillation disruptions on transionospheric transmissions. Ground-based ionosondes and GPS dual frequency receivers of the IGS network and other networks are limited to observations from land. This is particularly true in the Southern Hemisphere where the oceans cover most of the Hemisphere. Radio Occultation(RO) measurements are of only short duration and provide limited resolution over any given area. Ionospheric measurements derived from dual frequency GPS measurements on board a ship extends the coverage feasible with terrestrial and RO measurements.

Figure 1 shows the theoretical South Atlantic coverage of the coastal and island-based dual frequency GPS receivers for a 10° elevation angle cut-off, assuming an ionospheric peak density height, $h_mF2=350$ km. The coverage is here defined by the circular region within which all ionospheric pierce points are expected for GPS satellites observed from the specific land-based dual frequency receivers. Due to the 55° inclination angle of the GPS satellite orbits, the coverage of the high latitude GPS receivers would be somewhat less than predicted from the circular regions.

To supplement sparse *in situ* measurements of the ionosphere over this open ocean area of the South Atlantic Ocean, the Hermanus Magnetic Observatory (HMO) has undertaken an ionospheric measurement campaign employing a geodetic grade dual frequency GPS receiver on board the South African polar research ship, the SA Agulhas, for characterising the ionosphere along its routes to Antarctica and the Southern Ocean Islands serviced by the South African National Antarctic programme (SANAP). The routes of the SA Agulhas to the South Atlantic Islands, Gough (40°17'S, 9°58'W, Mag lat 42°S) and

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Marion ($46^{\circ}52'S$, $37^{\circ}51'E$, Mag lat $51^{\circ}S$) and to the Antarctic base SANAE IV at Vesleskarvet ($71^{\circ}40'S$, $2^{\circ}51'W$, Mag lat $61^{\circ}S$) present unique locations for investigating the variability of the upper atmosphere and its link with the near-Earth space environment.

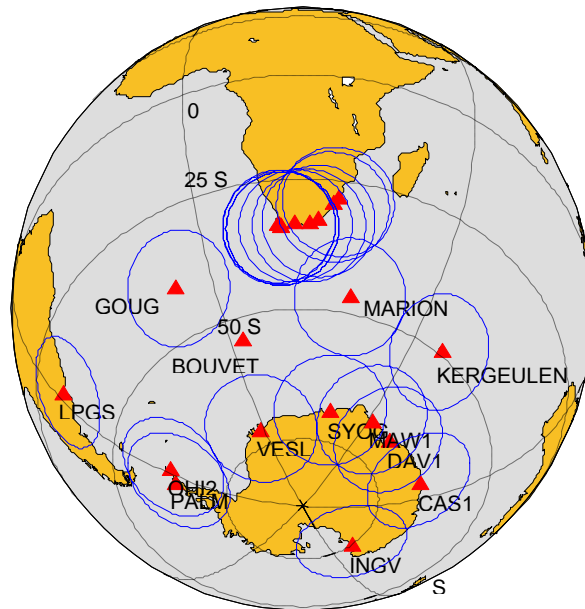


Figure 1: Theoretical South Atlantic coverage of the coastal and island-based dual frequency GPS receivers. A 10° elevation angle cut-off, and an ionospheric peak density height, $h_mF_2=350$ km, is assumed.

2.0 SOUTH ATLANTIC ANOMALY

The HMO manages a research project focusing on the interaction of the Earth's magnetic field with the ionized plasma in the upper atmosphere (80-2000 km altitude) above the South Atlantic Anomaly (SAA) and utilises ground and satellite-based sensors (Antarctic SHARE radar at Vesleskarvet, CHAMP satellite) for this purpose [1]. The interest in characterizing the ionosphere over this region stems from the observations that the Earth's magnetic field is decreasing in this region at an unprecedented rate and that the region is prone to increased ionospheric ionization by the precipitation of high energy particles from the Van Allen belts in the region of the decreased field of the SAA.

During the Earth's history, the geomagnetic north and south poles have reversed many times at intervals typically ranging from about 120 000 years to 660 000 years. A recent research report based on satellite data suggests that a reverse dynamo may be developing below the southern tip of Africa [2].

Figure 2 shows the change in the geomagnetic field over the period 1980 to 2001 as observed by the MAGSAT and CHAMP satellites. This region of large decrease in the geomagnetic field suggests that this decrease could eventually lead to a geomagnetic field reversal similar to the last known reversal 780 000 years ago and which is long overdue. South Africa is uniquely positioned to study these geomagnetic field changes and its effects on the magnetosphere and ionosphere.

A consequence of the severe reduction of the magnetic field in the SAA is that high energy particles of the hard radiation belt penetrate deeper into the upper atmosphere in the SAA than anywhere else on Earth. The hazards of this region appear to lack recognition outside the space science community,

although most spacecraft crossing this region at altitudes below 1000 km have experienced damage or degradation to some extent. Figure 3 shows the location of the SAA by means of contours of constant magnetic field intensity at 1338 km altitude together with sites of spacecraft anomalies in the area of the SAA as recorded on TOPEX and MODIS.

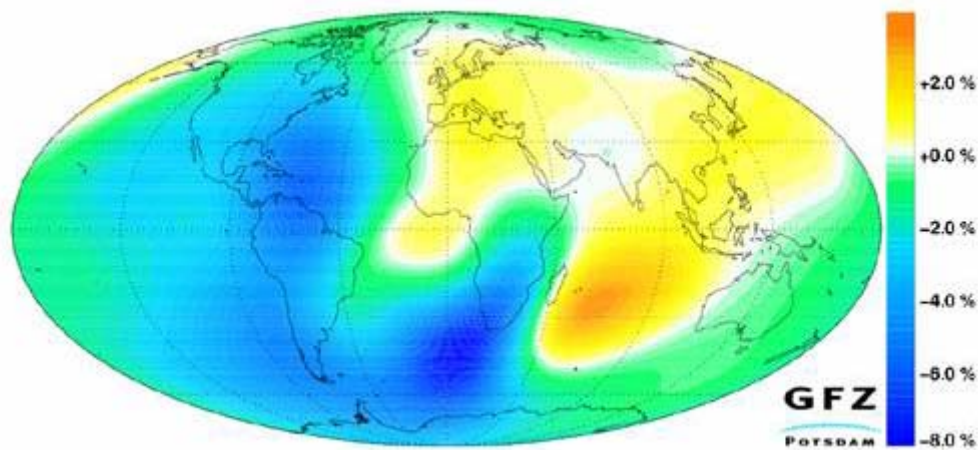


Figure 2: Percentage change of the geomagnetic total field intensity between 1980 and 2001, as measured by the Magsat and CHAMP satellites respectively. The largest decrease occurs in the region of the South Atlantic ocean between South Africa and Antarctica.

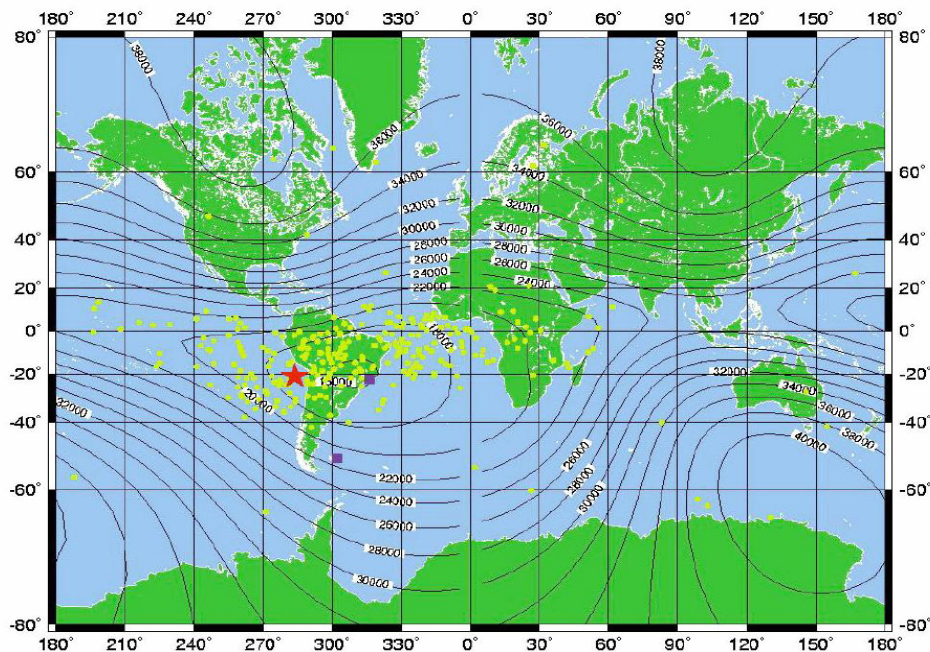


Figure 3: Contours of constant magnetic field intensity in nT at 1338 km altitude. Sites of spacecraft anomalies in the area of the SAA on TOPEX (dots) and MODIS (star) are indicated.

3.0 INTER-HEMISPHERIC COORDINATED MEASUREMENTS DURING IPY/IHY

The HMO, together with a consortium of institutions in South Africa with an interest in Space Weather is a participant in the campaign for coordinated inter-hemispheric high latitude ionospheric measurements during the international polar year (IPY) 2007-2008 and international Heliophysical year (IHY) 2007. A South African project, titled “Polar Space Weather Studies during IPY 2007” which was submitted to the IPY Science Committee by the authors of this paper in 2004, has recently been endorsed by the South African Minister of Science and Technology and is funded through the South African National Antarctic programme. One of the objectives of IPY/IHY is to conduct observations of the ionosphere and magnetosphere at geomagnetic conjugate locations in order to understand the North-South coupling between the manifestations of Heliospheric phenomena and their ionospheric effects. Conjugate campaigns have in the past produced very valuable data. Using conjugate measurements will allow a better understanding of ionospheric and geomagnetic activity as a function of solar wind plasma conditions. There is a unique opportunity for conjugate measurements by observations on board the SA Agulhas during its trips to the Southern Islands and Antarctica during IPY/IHY 2007-2008. In each case a significant part of the conjugate of the Southern hemisphere route maps to locations on land in the Northern Hemisphere where it may be feasible to conduct simultaneous coordinated measurements. Figure 4 to Figure 6 show the great circle routes of the SA Agulhas to various destinations in the South Atlantic and their conjugate routes in the Northern Hemisphere.

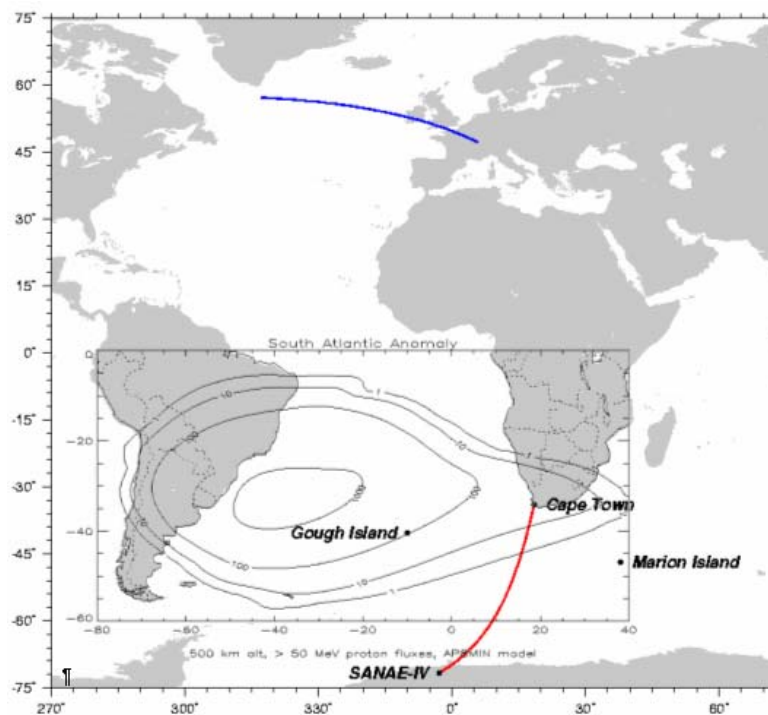


Figure 4: The direct route between Cape Town and SANA IV on Antarctica and its conjugate route in the Northern hemisphere

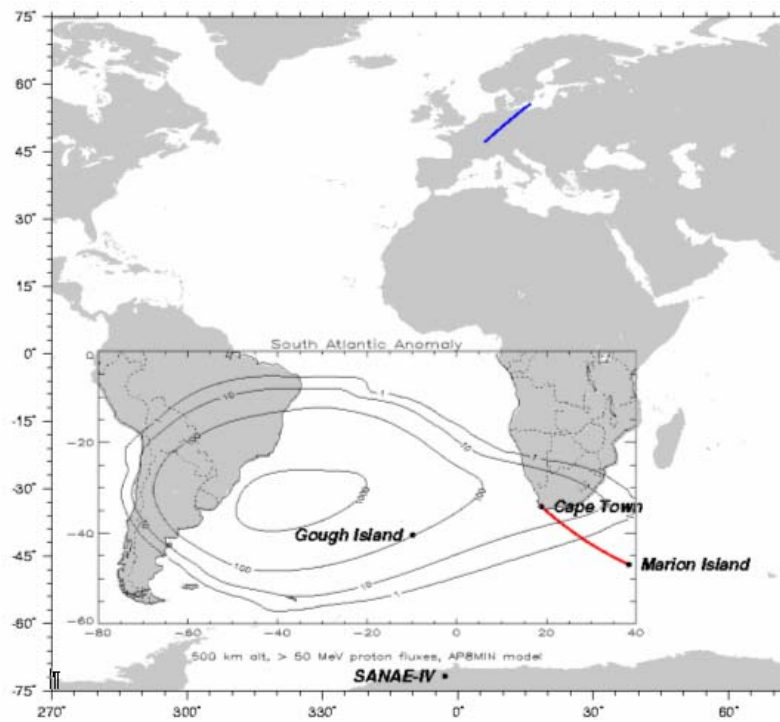


Figure 5: The direct route between Cape Town and Marion Island and its conjugate route in the Northern hemisphere.

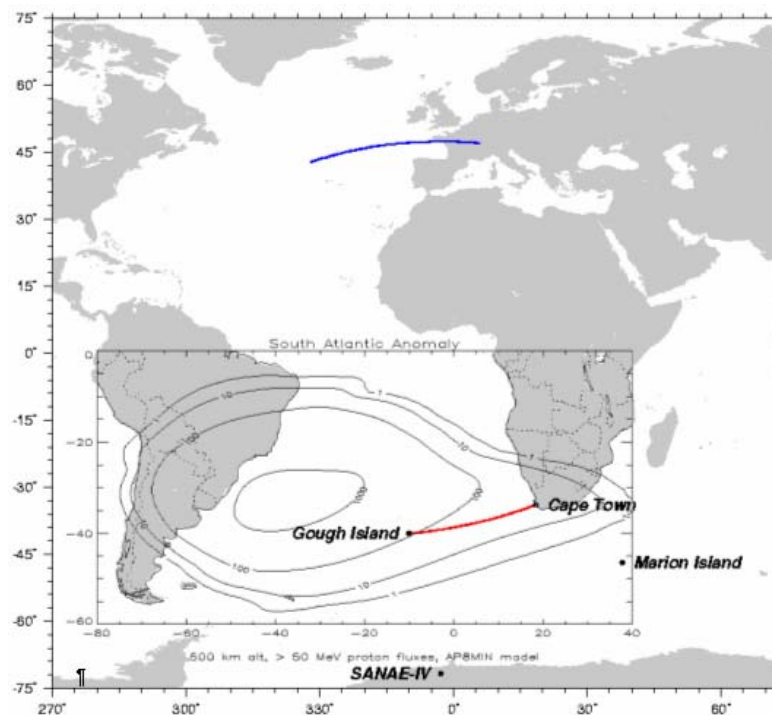


Figure 6: The direct route between Cape Town and Gough Island and its conjugate route in the Northern hemisphere.



Figure 7: Location of the GPS choke ring antenna on board the SA Agulhas. Inset shows antenna with radome.

4.0 GPS MEASUREMENTS ON BOARD THE SA AGULHAS

South Africa maintains bases at Antarctica (SANAE IV) as well as on Marion and Gough Islands. The SA Agulhas is South Africa's polar research vessel and is managed and administered by the Department of Environmental Affairs & Tourism (DEA&T). The Agulhas has been in service for almost thirty years. The Agulhas is used to service the three SANAP research bases in the Southern Ocean and Antarctica as well as various research voyages. Permission was obtained from the ship's operations manager to mount a GPS dual frequency receiver and a radome antenna on board the ship for all voyages since 1 December 2005. Figure 7 shows the location of the GPS antenna on board the SA Agulhas. The GPS receiver we installed is an Ashtech Z-FX geodetic grade dual frequency receiver, kindly loaned to the HMO for the Ionospheric Measurement Campaign (IMC) by the Chief Directorate Surveys and Mapping (CDSM) of South Africa. The receiver was set to sample the GPS observables P1, P2, C1, L1 and L2 at one second intervals. With the high data sampling rate it is anticipated that both TEC and scintillation events, using the ROTI index [3] could be derived. Dynamic 4D (lat, lon, height & time) electron density profiles are to be derived from the GPS measurements by means of full ionospheric tomographic inversion using the MIDAS programme [4]. The GPS antenna location was a compromise between finding a location with minimal vibration and movement in the wind, and a location that would be high enough above other structures on the deck to minimize their obscuring the ray paths from low-elevation GPS satellites.

The GPS receiver and antenna was tested with all the ships radars in operation. There was no indication of incompatibility of the GPS receiver and the ship's radar. The first recording campaign has taken place 1 December 2005 to 18 February 2006 during the journey of the SA Agulhas to the South African Antarctic base SANAE IV. The next trip during which the GPS Receiver was installed on the SA Agulhas was the trip to Marion Island 6 April to 11 May 2006. During its upcoming trip to Gough Island in September 2006, the SA Agulhas will come closest to the edge of the SAA.

5.0 DATA PROCESSING

GPS phase (L1 and L2) and pseudo range observables (P1 and P2) were logged as hourly binary RINEX files at 1 Hz using Thales' Geodetic Base Station Software (GBSS). The ships position was derived by logging all GPS NMEA messages separately as a daily ASCII file at 1 Hz using software developed in-house at the HMO. In post processing the hourly binary RINEX files were decimated to sixty-second RINEX ASCII files and concatenated into single twenty-four hour RINEX ASCII files. The GPS receiver position was extracted from the NMEA messages at sixty-second intervals, time-synchronised with the RINEX data and written to an ASCII file. The final product data used for ionospheric tomography comprised an ASCII RINEX file for each day of the trip, containing GPS observables and an ASCII file containing the receiver's geographic position, both sampled at sixty seconds spanning a twenty-four hour period.

The interfrequency bias of the SA Agulhas GPS receiver was estimated using MIDAS and referenced to all the other land-based GPS receivers that were operational on the days the SA Agulhas was anchored in the Cape Town harbour before its departure.

6.0 FUTURE OBJECTIVES

The 2005/2006 SA Agulhas Ionospheric Measurement campaign is a trial run for a two-year campaign that will form part of the ICESTAR/IPY proposal for IPY 2007/2008, and address the following three main themes:

- coupling processes between the different atmospheric layers and their connection with the solar activity,
- energy and mass exchange between the ionosphere and the magnetosphere, and
- Inter-hemispheric similarities and asymmetries in Geospace phenomena.

Simultaneous ionospheric measurements at geomagnetic conjugate sites in the Northern Hemisphere are envisaged during IPY.

In the near future GPS derived ionospheric electron density distribution calculated by means of the MIDAS programme and TEC distributions calculated by means of a spherical harmonic interpolation [5] derived from the SA Agulhas data are to be compared to the IRI model and confirmed by occultations observed by the CHAMP satellite. The results from this analysis would be of interest to the ionospheric modelling community as well as for the prediction of propagation conditions in the auroral regions. GPS ionospheric maps to be derived from this campaign are considered to be of great help for better understanding of the complex ionospheric environment and the global response of the ionosphere to geomagnetic storms.

7.0 RESULTS

Figure 8 shows a plot of the ground traces of ionospheric pierce points (IPPs) of all ray paths to GPS satellites observed with the GPS receiver on board the SA Agulhas during a 12 hour period preceding its

departure from the harbour in Cape Town. This illustrates the lack of coverage over South Atlantic even by a coastal GPS receiver. Figure 9 shows a plot of the corresponding observations on an elevation-azimuth plot. This illustrates the smokestack obscuring satellites below 60° elevation for an azimuth range of about 80° ranging from 140° to 220°. The ship's bow was pointed approximately South-East at the time of this recording.

Figure 10 shows the theoretical IPP range of GPS coverage for the recorded routes during the voyages of the SA Agulhas from Cape Town to Antarctica (1-20 Dec 2005), Marion Island (5 April to 11 May 2006) and Gough Island (15 Sep -11 Oct 2005) using 10 degree elevation cut-off and an ionospheric shell height of 350 km. These coverage circles were calculated assuming a symmetric coverage area around the receiver. Due to the inclination of the GPS satellite orbits the coverage to the South of each location is likely to be less than the coverage to the North.

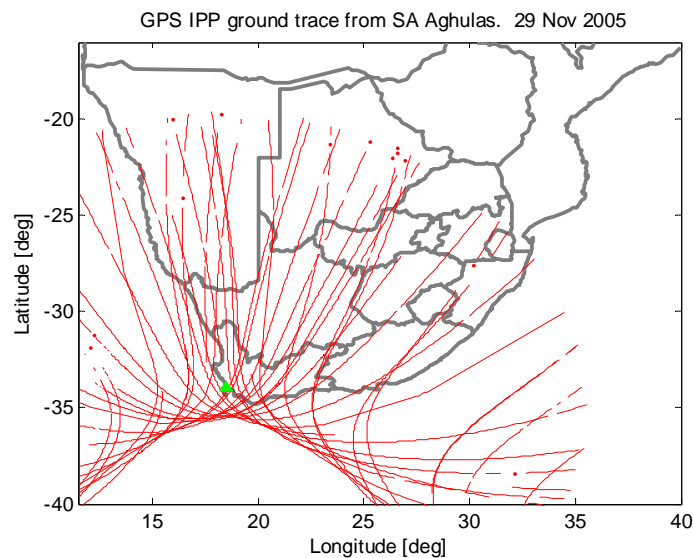


Figure 8: GPS IPP ground traces for satellites observed from the GPS receiver on board the SA Agulhas during a 24 hour period on 29 November 2005.

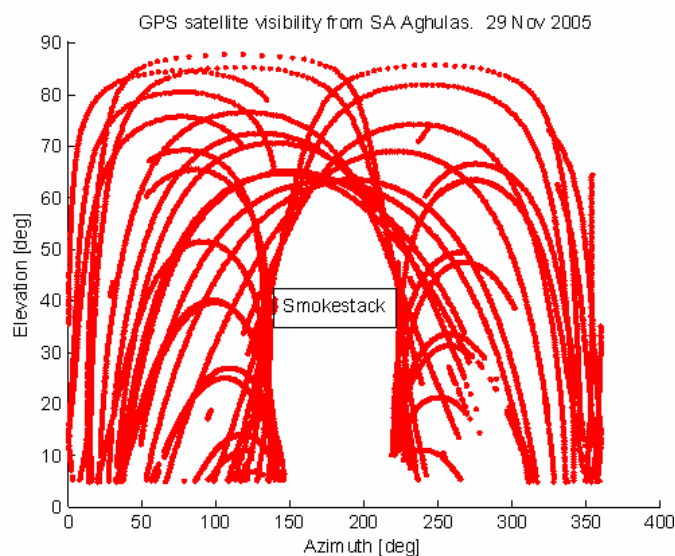


Figure 9: GPS observations on 29 November on an elevation-azimuth plot.

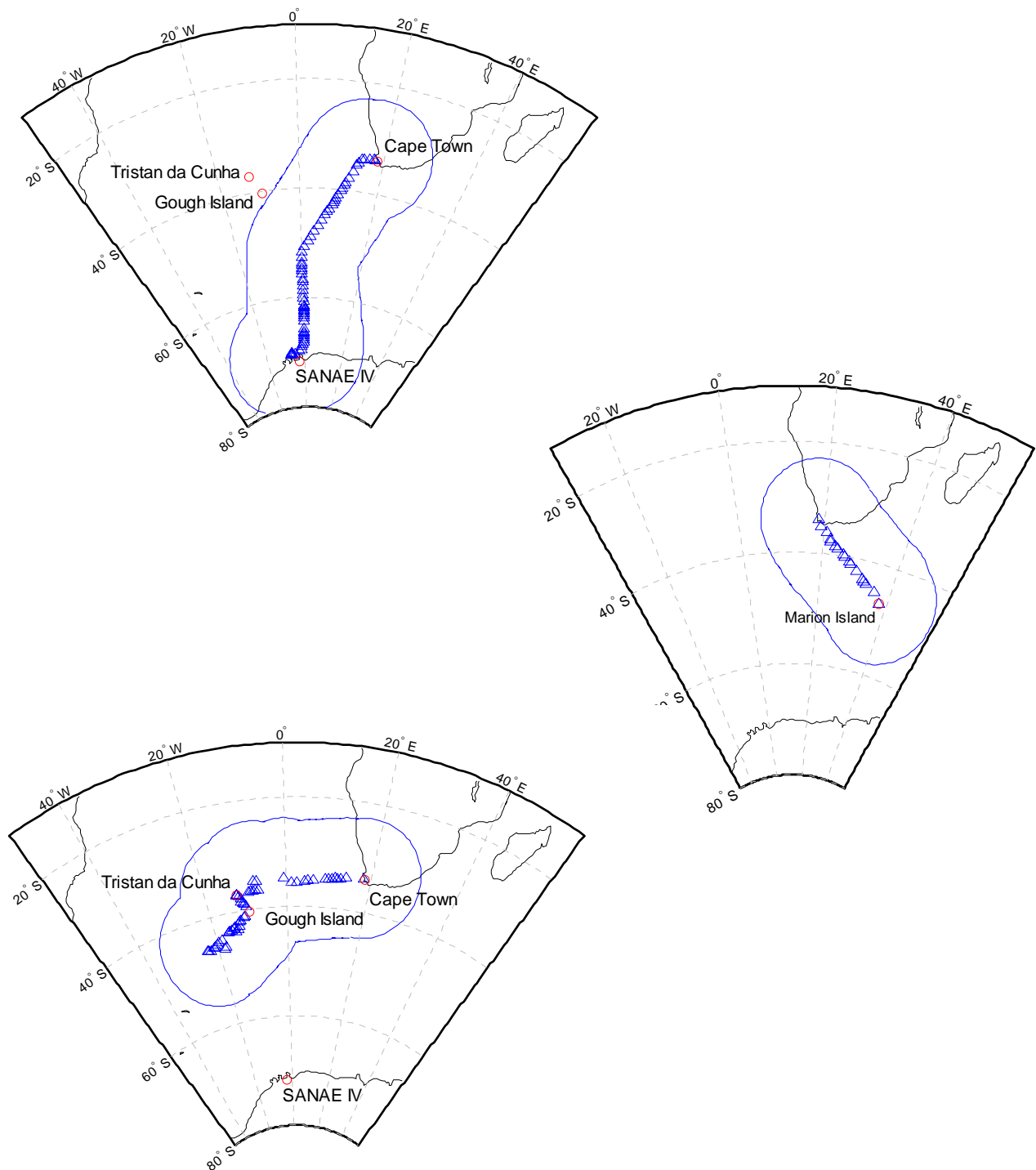


Figure 10: Theoretical IPP range of GPS coverage for recorded routes of SA Agulhas voyages from Cape Town to Antarctica (1-20 Dec 2005), Marion Island (5 April to 11 May 2006) and Gough Island (15 Sep -11 Oct 2005) using 10 degree elevation cut-off and an ionospheric shell height of 350 km.

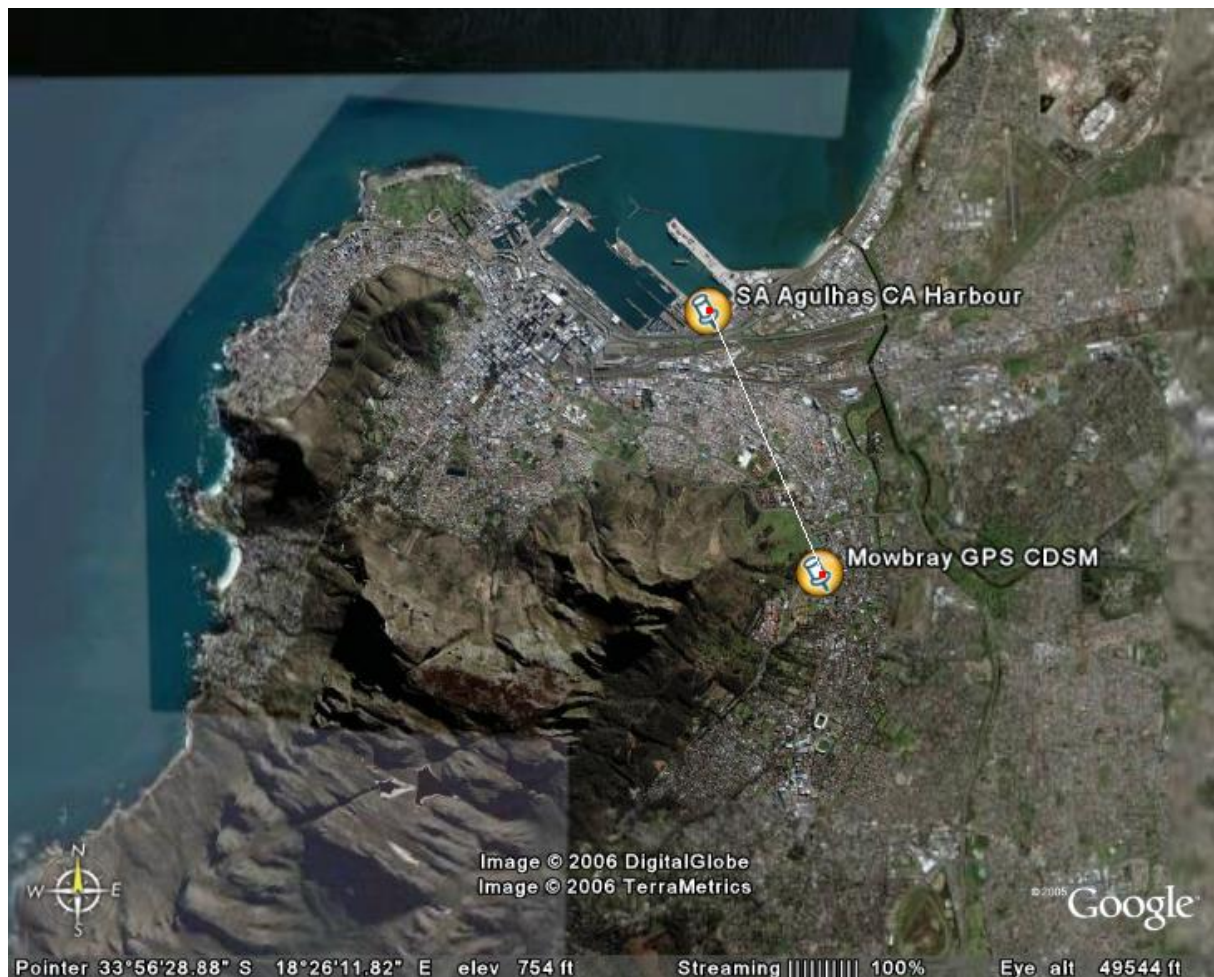


Figure 11: Map with SA Agulhas docking location in the Cape Town Harbour and the nearest fixed GPS receiver location at the headquarters of the Chief Directorate Surveys and Mapping (CDSM) in Mowbray Cape Town, 4 km South East of the docking location. The bow of the SA Agulhas was directed South-East while docked in the harbour. (Credit GoogleEarth)

Figure 11 shows a map with the SA Agulhas docking location in the Cape Town Harbour and the nearest fixed GPS receiver location at the headquarters of the Chief Directorate Surveys and Mapping (CDSM) in Mowbray Cape Town, about 4 km South of the docking location. The bow of the SA Agulhas was directed South-East while docked in the harbour. The multipath noise on the P1-observable, the TEC, and vertical electron density values derived from the data obtained with the GPS receiver on board the SA Agulhas were compared with that of the fixed GPS station in Mowbray.

The biases determined from the GPS data for the 12 hours of December 1 when the ship was anchored in the Cape Town Harbour are shown in Figure 12. The interfrequency bias of the SA Agulhas was 7 TECU, which is of the same order of the biases for the 26 fixed receivers that were operational at the same time. The standard deviation of the SA Agulhas bias was negligible compared to that of the other receivers.

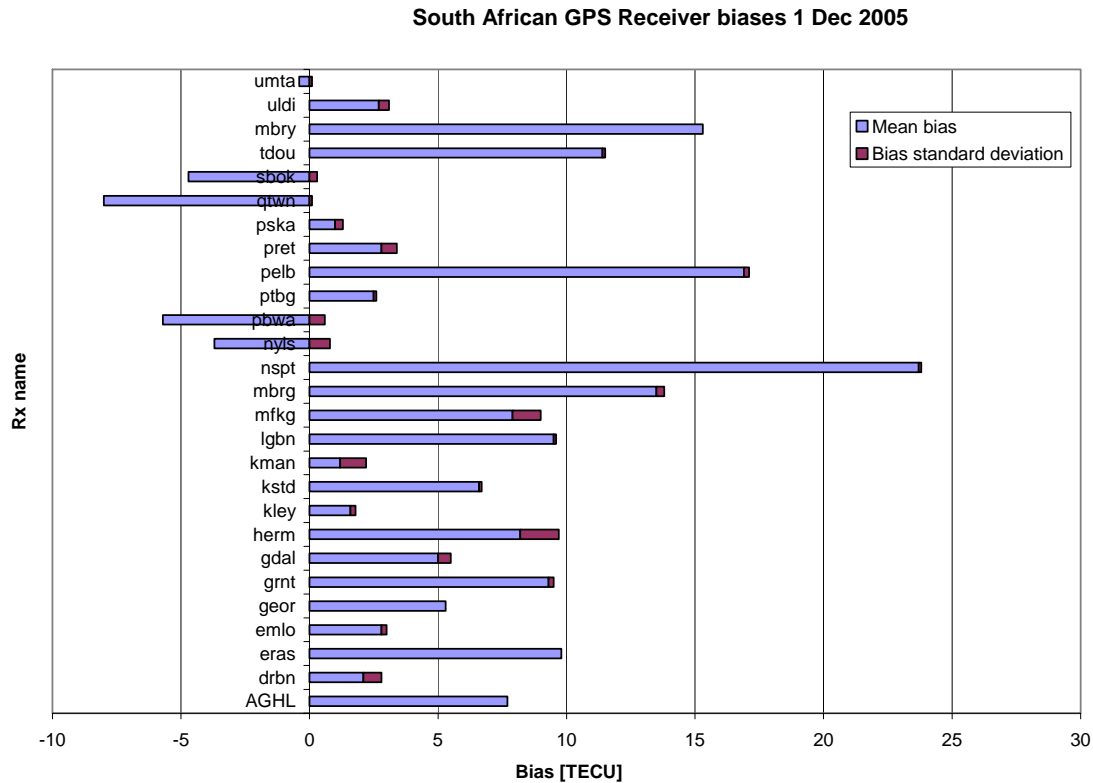


Figure 12: GPS receiver biases for the SA Agulhas receiver (AGHL) together with the biases of all the other receivers in the CDSM network which were operational during the period midnight to noon on 1 December 2005, which the SA Agulhas was anchored on the Cape Town harbour.

Figure 13 shows the logged latitude, longitude and speed of the GPS Receiver on board the SA Agulhas on the day of its departure from the Cape Town harbour. Note that the position was steady until it started moving out of the harbour at 12:00 LT. This test confirmed the correct operation of the logged NMEA position data. The GPS bias estimation was done during the steady period up to departure. The cruising speed of the ship is about 20 km/h, i.e. 480 km/day, 333 m/min or 5 m/s.

Figure 14 shows a TEC map at 12:00 UT (13:20 LT) over the Southern tip of Africa obtained by tomographic inversion using MIDAS. The input was one hour of GPS data recorded by the GPS receiver on board the SA Agulhas while still in the Cape Town Harbour. Figure 15 shows a comparative TEC map using GPS data recorded by the fixed GPS receiver at the Cape Town GPS station in Mowbray, about 4 km south east of where the SA Agulhas was anchored in the Cape Town Harbour. The Mowbray data was sub-sampled to 30 s intervals for the comparative inversion. Note the similarity of the TEC maps which confirms the correct operation of the GPS Receiver on board the SA Agulhas.

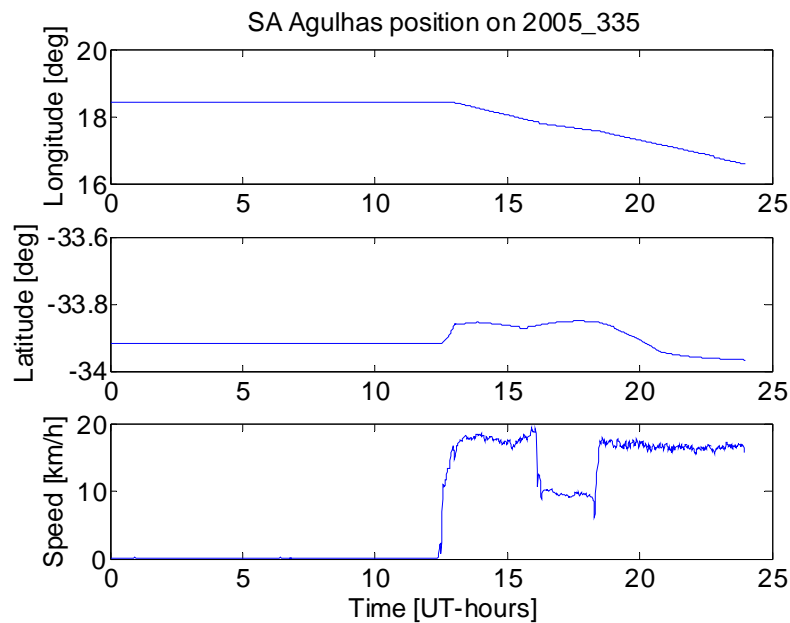


Figure 13: Coordinates and speed logged at 1 minute intervals on the GPS receiver on board the SA Agulhas on the day of first departure from the Cape Town Harbour after installation of the dual frequency GPS receiver on board the ship.

Figure 16 gives a comparison of vertical TEC over the MBRY GPS station derived by MIDAS first from 24 hours of GPS data recorded on the SA Agulhas and then from GPS data recorded at the Mowbray fixed receiver while the SA Agulhas was anchored in the Cape Town Harbour on 1 December 2005. Note the close correlation of the TEC values.

Figure 17 presents P1-P2 in m for land and ship-based GPS receivers. Satellite numbers run from left to right, then top to bottom. The data used for this bias estimation was recorded on 1 December 2005 while the ship was in the harbour. The SA Agulhas data shows a larger variation, probably due to multipath and sporadic P1-P2 values which are marked in red.

Figure 18 presents the Ionospheric Pierce Points (IPPs) at hourly intervals for all satellite ray paths observed along the route of the SA Agulhas on its first trip to Antarctica (1-14 Dec 2005) during which measurements were made of the ionosphere over the South Atlantic Ocean using a GPS dual frequency receiver on board the ship.

Figure 19 presents the 2D electron density distribution from 25° to 75° South along the 0° meridian as determined from the MIDAS inversion of the SA Agulhas GPS data of 7 December 2005 when the ship was about halfway between Cape Town (35°S) and Antarctica (75°S). Note the interesting high latitude structure resolved by the inversion.

Figure 20 presents the IPPs at one minute intervals for all satellite ray paths observed along the route of the SA Agulhas on its first trip to Marion Island (6-12 Apr 2006) after being equipped with a dual frequency GPS receiver.

Figure 21 shows a TEC-map over the South Atlantic Ocean for 10:00 UT on 12 Apr 2006, generated from the tomographic inversion of the data recorded on the SA Agulhas during its trip to Marion Island.

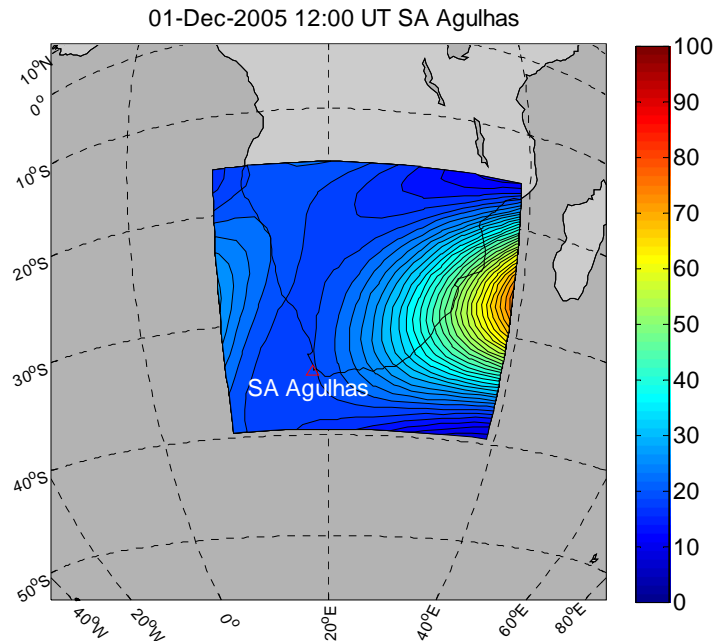


Figure 14: SA Agulhas TEC map at 10:00 UT (11:20 LT) obtained by tomographic inversion using MIDAS with input one hour of GPS data recorded by the GPS receiver on board the SA Agulhas while in the Cape Town Harbour. The data was sub-sampled to 1 minute intervals for the inversion.

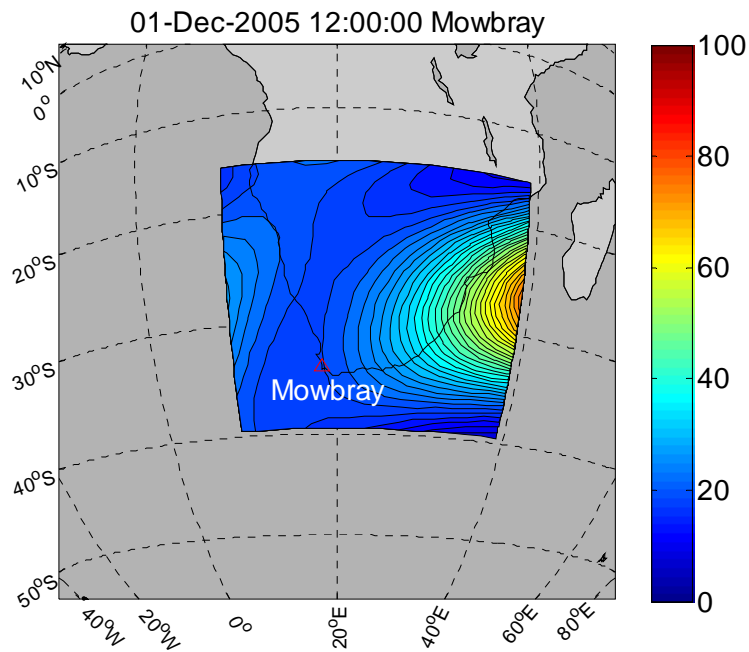


Figure 15: Mowbray TEC map at 12:00 UT (13:20 LT) obtained by tomographic inversion using MIDAS with input one hour of GPS data recorded by the GPS receiver at the fixed Cape Town GPS station in Mowbray, about 4 km South of where the SA Agulhas was anchored in the Cape Town Harbour. The data was sub-sampled to 30 s intervals for the inversion.

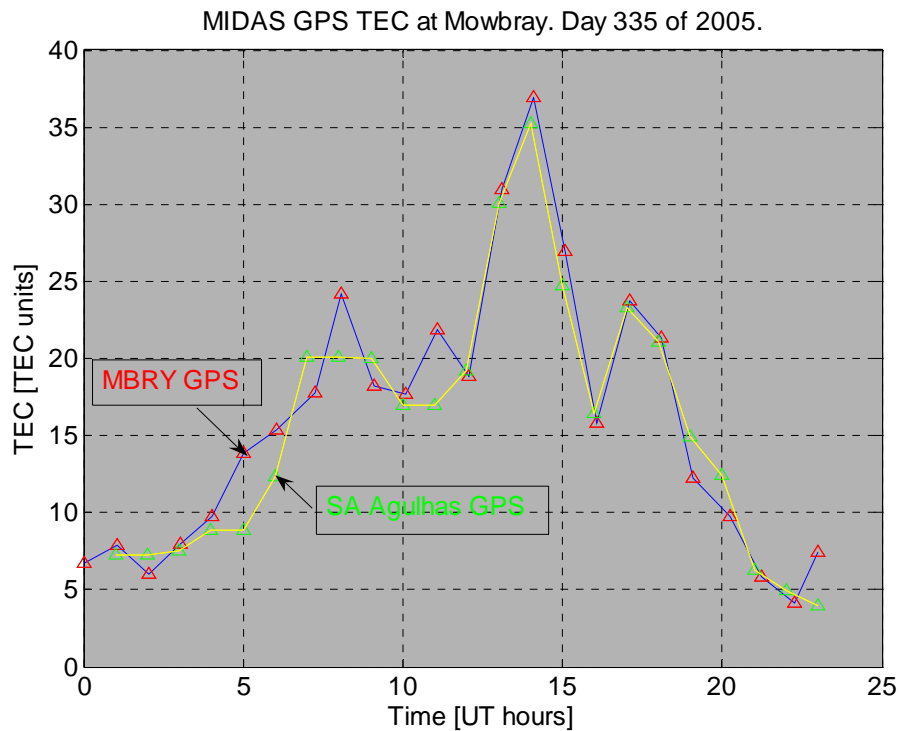


Figure 16: A comparison of vertical TEC over the MBRY GPS station derived by MIDAS first from 24 hours of GPS data recorded on the SA Agulhas and then from GPS data recorded at the Mowbray fixed receiver while the SA Agulhas was anchored in the Cape Town Harbour on 1 December 2005. Note the close correlation of the TEC values.

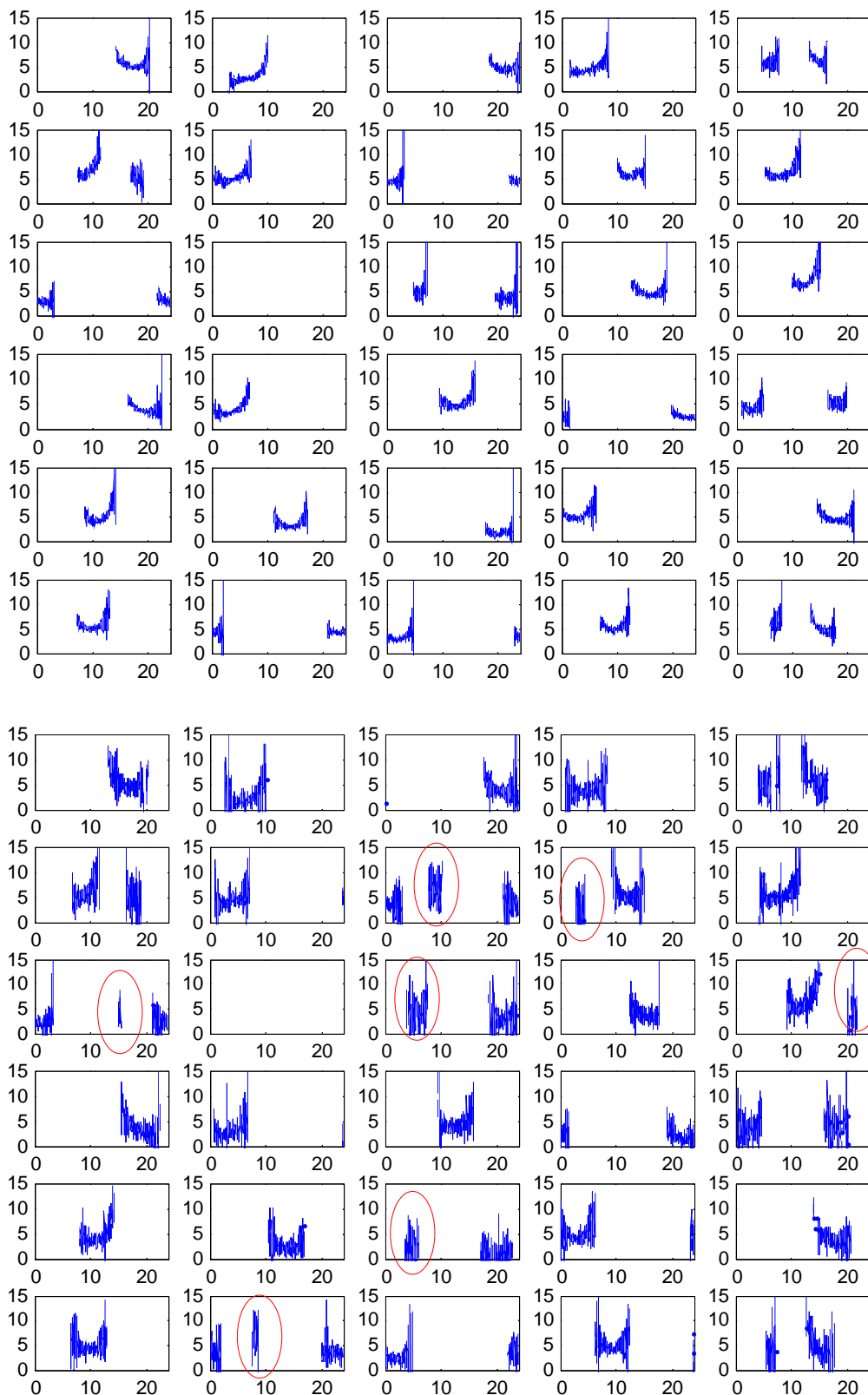


Figure 17: P1-P2 in m for land and ship-based GPS receivers. Satellite numbers run from left to right, then top to bottom. Data recorded on 1 December 2005 while the ship was in the harbour.

Top = Mowbray, Bottom = SA Agulhas. The SA Agulhas data shows a larger variation, probably due to multipath and sporadic P1-P2 values which are marked in red.

SA Agulhas trajectory from 01-Dec-2005 12:00:00 to 14-Dec-2005 10:00:00

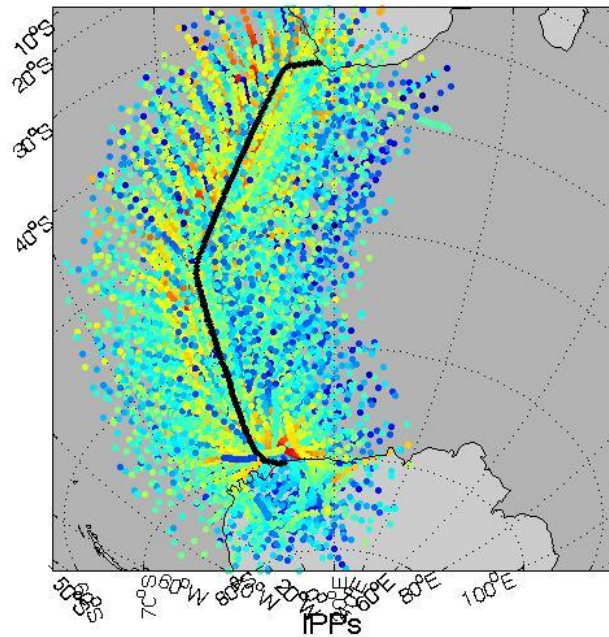


Figure 18: Ionospheric Pierce Points (IPPs) at hourly intervals for all satellite ray paths observed along the route of the SA Agulhas on its first trip to Antarctica (1-14 Dec 2005) during which measurements were made of the ionosphere over the South Atlantic Ocean using a GPS dual frequency receiver on board the ship. The colours indicate the slant TEC along the ray paths.

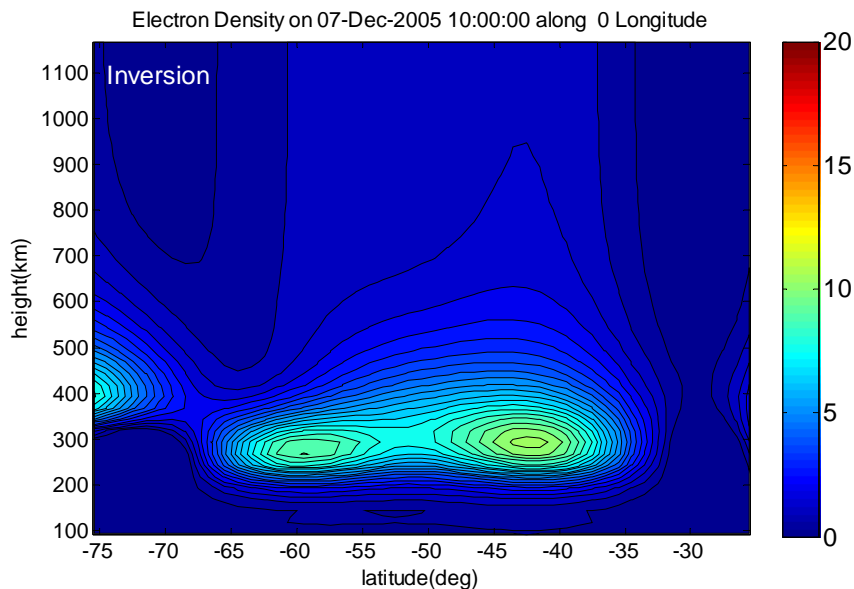


Figure 19: Electron density distribution along the 0° meridian as determined from the MIDAS inversion of the SA Agulhas GPS data of 7 December 2005 when the ship was about halfway between Cape Town (35° S) and Antarctica (75° S). The electron density is in units of $10^{12}/\text{m}^3$. Note the interesting high latitude structure resolved by the tomographic inversion.

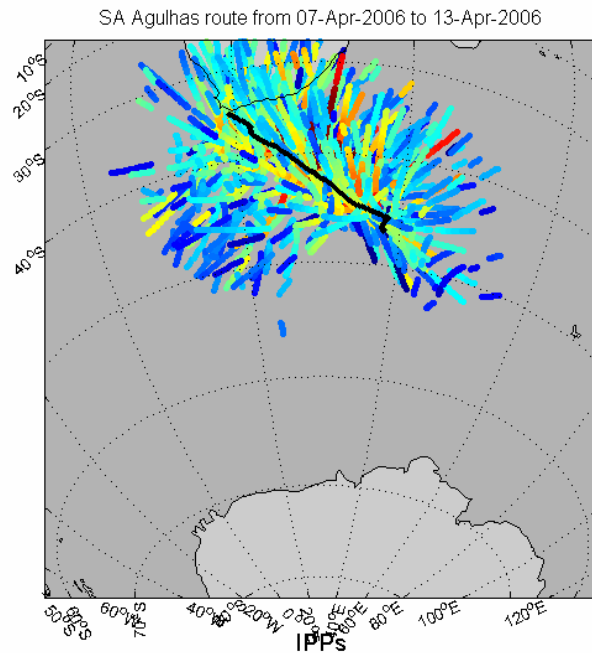


Figure 20: The IPPs at one minute intervals for all satellite ray paths observed along the route of the SA Agulhas on its first trip to Marion Island (6-12 Apr 2006) after being equipped with a dual frequency GPS receiver.

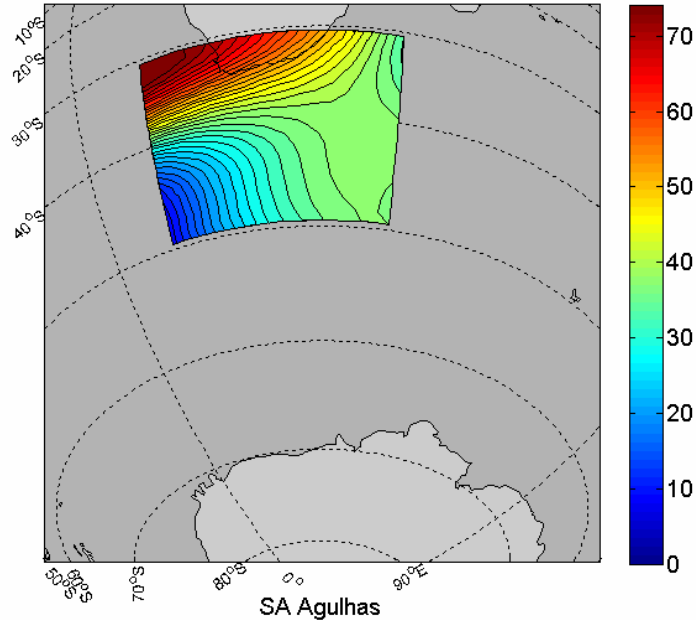


Figure 21: A TEC-map over the South Atlantic Ocean for 10:00 UT on 12 Apr 2006, generated from the tomographic inversion of the data recorded on the SA Agulhas during its trip to Marion Island. The colour bar shows TEC in TECU ($10^{16}/m^2$).

8.0 CONCLUSION

The characterisation of the ionosphere using ship-based dual frequency GPS receivers have the potential to provide valuable inputs to local and global models for the prediction of ionospheric behaviour, especially in regions not well charted by terrestrial GPS receivers. The present paper illustrates some of the problems of locating a GPS receiver on a research ship and provides some results obtained by computerised ionospheric tomography by means of the MIDAS programme to demonstrate the benefit of this novel approach. This work may lay the basis for equipping more research and other ships with dual frequency GPS receivers to complement the characterization of the ionosphere by means of terrestrial GPS receivers and GPS receivers on board satellites in low earth orbit.

9.0 ACKNOWLEDGEMENTS

The South African National Antarctic Programme (SANAP) is acknowledged for facilitating the installation of the GPS receiver and antenna on board the SA Agulhas. The authors gratefully acknowledge the Chief Directorate Surveys and Mapping of South Africa for making available the GPS receiver and antenna placed on board the SA Agulhas for the campaigns reported here and for making available the GPS data from the Mowbray receiver station. Dr Andrew Collier assisted with the computation of the geomagnetic conjugates of the great circle routes of the SA Agulhas.

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